Fourth-order Correlations of Conserved Charges in the QCD Thermodynamics

Wei-jie Fu[1,∗] and Yue-liang Wu[1,†]

[1]*Kavli Institute for Theoretical Physics China (KITPC),*

Key Laboratory of Frontiers in Theoretical Physics, Institute of Theoretical Physics,

Chinese Academy of Science, Beijing 100190, China

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Abstract

The fourth-order correlations of conserved charges, such as the baryon number, electric charge, and strangeness, are studied at finite temperature and nonzero baryon chemical potential in an effective model. It is found that the fourth-order correlations change rapidly and have three extrema during the chiral crossover with the increase of the baryon chemical potential. The absolute values of the extrema approach infinity when the thermodynamical system moves toward the QCD critical point and the fourth-order correlations are divergent at the critical point. The contour plots of the fourth-order correlations in the plane of the temperature and baryon chemical potential are given. It is noticed that all the fourth-order correlations of conserved charges, except for χ_{13}^{BS} and χ_{13}^{QS}, are excellent probes to explore the QCD critical point in heavy ion collision experiments.

∗wjfu@itp.ac.cn

†ylwu@itp.ac.cn

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It is believed that the deconfined quark gluon plasma (QGP) is produced in ultrarelativistic heavy ion collisions [1–8]. Therefore, QCD thermodynamics, such as the equation of state of the QGP, chiral and deconfinement phase transitions, QCD phase diagram and so on, has been a subject of intensive investigation in recent years. One distinct characteristic of the QCD thermodynamics is that there is a critical point in the QCD phase diagram in the plane of temperature and baryon chemical potential, which separates the first-order phase transition at high baryon chemical potential from the continuous crossover at high temperature [9]. This characteristic is confirmed in various field theory models [10–18]. Although there is no definite evidence that the QCD critical point also exists in the lattice QCD calculations due to the sign problem at finite chemical potential, some lattice groups find that the QCD critical point maybe exist in the phase diagram, based on extrapolating results at small μ_B/T (ratio of the baryon chemical potential and the temperature) to those at large μ_B/T [19–21]. In the meantime, experiments with the goal to search for the QCD critical point are planned and underway at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory (BNL) and at the Super Proton Synchrotron (SPS) at CERN in Geneva [22–25].

Then, searching for and locating the QCD critical point becomes a crucial and vital task. It has been proposed that the QCD critical point can be found through the non-monotonic behavior of fluctuations and correlations of various particle multiplicities as functions of varying control parameters [26–36]. Particularly, fluctuations and correlations of conserved charges, such as the baryon number, electric charge, and strangeness, deserve more attentions. On the one hand, the fluctuations and correlations of conserved charges are sensitive to the structure of the thermal strongly interacting matter and behave differently between the hadronic and QGP phases [16, 26, 27, 31, 37]. On the other hand, since the conserved charges are conserved through the evolution of the fire ball, the fluctuations and correlations of conserved charges can be measured in heavy ion collision experiments.

In our previous work [38], we have calculated the fluctuations of conserved charges up to the fourth-order and the correlations to the third-order at finite temperature and nonzero baryon chemical potential in the 2+1 flavor Polyakov–Nambu–Jona-Lasinio (PNJL) model. We found an interesting result: among all the fluctuations and correlations discussed in our previous work [38], the numerical calculations indicate that χ_{21}^{BQ}, χ_{21}^{BS}, χ_{21}^{QS}, and χ_{111}^{BQS} (those notations will be introduced in the following) are the most valuable probes for exploring the

QCD critical point. All these quantities are the third-order correlations of conserved charges. Therefore, it is natural to go beyond our previous work to study the fourth-order correlations of conserved charges near the QCD critical point. Furthermore, using higher-order moments of particle multiplicity distributions to search for the QCD critical point is possible in the Beam Energy Scan at RHIC [24]. In this work, we will calculate the fourth-order correlations of conserved charges at finite temperature and nonzero baryon chemical potential in the PNJL model. Most attentions will be paid on the studies of the non-monotonic behavior of the fourth-order correlations near the QCD critical point.

We begin with the definition of the correlations of conserved charges as follows

$$\chi_{ijk}^{BQS} = \frac{\partial^{i+j+k}(P/T^4)}{\partial(\mu_B/T)^i \partial(\mu_Q/T)^j \partial(\mu_S/T)^k}, \tag{1}$$

where P and T is the pressure and temperature of a thermodynamical system; $\mu_{B,Q,S}$ are the chemical potentials for baryon number, electric charge, and strangeness, respectively. These conserved charge chemical potentials are related with the quark chemical potentials through the following relations,

$$\mu_u = \frac{1}{3}\mu_B + \frac{2}{3}\mu_Q, \quad \mu_d = \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q, \quad \text{and} \quad \mu_s = \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q - \mu_S. \tag{2}$$

where $\mu_{u,d,s}$ are the chemical potentials for u, d, and s quarks, respectively. Denoting the ensemble average of conserved charge number N_X ($X = B, Q, S$) with $\langle N_X \rangle$, we can obtain the fourth-order correlations as follow

$$\chi_{13}^{XY} = \frac{1}{VT^3}\Big(\langle \delta N_X \delta N_Y^3 \rangle - 3\langle \delta N_X \delta N_Y \rangle \langle \delta N_Y^2 \rangle\Big), \tag{3}$$

$$\chi_{22}^{XY} = \frac{1}{VT^3}\Big(\langle \delta N_X^2 \delta N_Y^2 \rangle - \langle \delta N_X^2 \rangle \langle \delta N_Y^2 \rangle$$
$$-2\langle \delta N_X \delta N_Y \rangle^2\Big), \tag{4}$$

$$\chi_{211}^{XYZ} = \frac{1}{VT^3}\Big(\langle \delta N_X^2 \delta N_Y \delta N_Z \rangle - 2\langle \delta N_X \delta N_Y \rangle \langle \delta N_X \delta N_Z \rangle$$
$$-\langle \delta N_X^2 \rangle \langle \delta N_Y \delta N_Z \rangle\Big), \tag{5}$$

where $\delta N_X \equiv N_X - \langle N_X \rangle$ and V is the volume of the system.

We adopt the 2+1 flavor Polyakov-loop improved NJL model to study the fourth-order correlations of conserved charges near the QCD critical point. The validity of this effective model is expected, since the critical behavior of the QCD phase transition is governed by the universality class of the chiral symmetry, which is kept in this model. Furthermore,

compared with the conventional Nambu–Jona-Lasinio model, the PNJL model not only has the chiral symmetry and its dynamical breaking mechanism, but also includes the effect of color confinement through the Polyakov loop [18, 39–46]. Furthermore, the fluctuations and correlations of conserved charges calculated in the 2+1 flavor PNJL model at finite temperature but with vanishing chemical potentials in Ref. [36] are well consistent with those obtained in lattice calculations [47], which shows that the 2+1 flavor PNJL model is well applicable to study the cumulants of conserved charge multiplicity distributions.

The Lagrangian density for the 2+1 flavor PNJL model is given as [18]

$$\mathcal{L}_{\mathrm{PNJL}} = \bar{\psi}(i\gamma_\mu D^\mu + \gamma_0\hat{\mu} - \hat{m}_0)\psi + G\sum_{a=0}^{8}\left[(\bar{\psi}\tau_a\psi)^2 + (\bar{\psi}i\gamma_5\tau_a\psi)^2\right]$$
$$-K\left[\det_f(\bar{\psi}(1+\gamma_5)\psi) + \det_f(\bar{\psi}(1-\gamma_5)\psi)\right] - \mathcal{U}(\Phi,\Phi^*,T), \tag{6}$$

where $\psi = (\psi_u, \psi_d, \psi_s)^T$ is the three-flavor quark field, and

$$D^\mu = \partial^\mu - iA^\mu \quad \text{with} \quad A^\mu = \delta_0^\mu A^0 \quad, \quad A^0 = g\mathcal{A}_a^0\frac{\lambda_a}{2} = -iA_4, \tag{7}$$

where λ_a's are the Gell-Mann matrices in color space and g is the gauge coupling strength. $\hat{m}_0 = \mathrm{diag}(m_0^u, m_0^d, m_0^s)$ is the three-flavor current quark mass matrix. Throughout this work, we take $m_0^u = m_0^d \equiv m_0^l$, while keep m_0^s being larger than m_0^l, which breaks the $SU(3)_f$ symmetry. The matrix $\hat{\mu} = \mathrm{diag}(\mu_u, \mu_d, \mu_s)$ denotes the quark chemical potentials which are related with the conserved charge chemical potentials through relations in Eq.(2).

In the above PNJL Lagrangian, $\mathcal{U}(\Phi, \Phi^*, T)$ is the Polyakov-loop effective potential, which is expressed in terms of the traced Polyakov-loop $\Phi = (\mathrm{Tr}_c L)/N_c$ and its conjugate $\Phi^* = (\mathrm{Tr}_c L^\dagger)/N_c$ with the Polyakov-loop L being a matrix in color space given explicitly by

$$L(\vec{x}) = \mathcal{P}\exp\left[i\int_0^\beta d\tau\, A_4(\vec{x},\tau)\right] = \exp[i\beta A_4], \tag{8}$$

with $\beta = 1/T$ being the inverse of temperature and $A_4 = iA^0$.

In our work, we use the Polyakov-loop effective potential which is a polynomial in Φ and Φ^* [42], given by

$$\frac{\mathcal{U}(\Phi,\Phi^*,T)}{T^4} = -\frac{b_2(T)}{2}\Phi^*\Phi - \frac{b_3}{6}(\Phi^3 + \Phi^{*3}) + \frac{b_4}{4}(\Phi^*\Phi)^2, \tag{9}$$

with

$$b_2(T) = a_0 + a_1\left(\frac{T_0}{T}\right) + a_2\left(\frac{T_0}{T}\right)^2 + a_3\left(\frac{T_0}{T}\right)^3. \tag{10}$$

The parameters in the effective potential are fitted to reproduce the thermodynamical behavior of the pure-gauge QCD obtained from the lattice simulations, and their values are $a_0 = 6.75$, $a_1 = -1.95$, $a_2 = 2.625$, $a_3 = -7.44$, $b_3 = 0.75$, and $b_4 = 7.5$. The parameter T_0 is the critical temperature for the deconfinement phase transition to take place in pure-gauge QCD and T_0 is chosen to be $270\,\mathrm{MeV}$ according to the lattice calculations. As for the five parameters in the quark sector of the model, we adopt their values which are $m_0^l = 5.5\,\mathrm{MeV}$, $m_0^s = 140.7\,\mathrm{MeV}$, $G\Lambda^2 = 1.835$, $K\Lambda^5 = 12.36$, and $\Lambda = 602.3\,\mathrm{MeV}$, which are fixed by fitting the observables $m_\pi = 135.0\,\mathrm{MeV}$, $m_K = 497.7\,\mathrm{MeV}$, $m_{\eta'} = 957.8\,\mathrm{MeV}$, and $f_\pi = 92.4\,\mathrm{MeV}$ [48].

In the mean field approximation, the thermodynamical potential density $(\Omega = -P)$ for the 2+1 flavor quark system is given by

$$
\begin{aligned}
\Omega \;=\; & -2N_c \sum_{f=u,d,s} \int \frac{d^3 p}{(2\pi)^3} \Big\{ E_p^f \theta(\Lambda^2 - p^2) \\
& + \frac{T}{3} \ln\left[1 + 3\Phi^* e^{-(E_p^f - \mu_f)/T} + 3\Phi e^{-2(E_p^f - \mu_f)/T} + e^{-3(E_p^f - \mu_f)/T}\right] \\
& + \frac{T}{3} \ln\left[1 + 3\Phi e^{-(E_p^f + \mu_f)/T} + 3\Phi^* e^{-2(E_p^f + \mu_f)/T} + e^{-3(E_p^f + \mu_f)/T}\right] \Big\} \\
& + 2G(\phi_u{}^2 + \phi_d{}^2 + \phi_s{}^2) - 4K\phi_u\,\phi_d\,\phi_s + \mathcal{U}(\Phi, \Phi^*, T),
\end{aligned}
\tag{11}
$$

where ϕ_i's $(i = u, d, s)$ are the quark chiral condensates, and the energy-momentum dispersion relation is $E_p^i = \sqrt{p^2 + M_i^2}$, with the constituent mass being

$$
M_i = m_0^i - 4G\phi_i + 2K\phi_j\,\phi_k.
\tag{12}
$$

Minimizing the thermodynamical potential in Eq. (11) with respective to ϕ_u, ϕ_d, ϕ_s, Φ, and Φ^*, we obtain a set of equations for the minimal conditions, which can be solved as functions of temperature T and three conserved charge chemical potentials μ_B, μ_Q, and μ_S.

We use the method of Taylor expansion to compute the fourth-order correlations of conserved charges in the PNJL model. In Fig. 1 we show the fourth-order correlations between two conserved charges versus the baryon chemical potential at several values of temperature calculated in the PNJL model. We find that the QCD critical point is located at about $T_c = 160\,\mathrm{MeV}$ and $\mu_{B_c} = 819\,\mathrm{MeV}$ ($\mu_Q = \mu_S = 0$) with input parameters given above. From Fig. 1, one can clearly see that the magnitudes of all the fourth-order correlations in this figure grow rapidly and oscillate drastically when the QCD phase transition occurs. Comparing different curves corresponding to different temperatures, we can recognize that
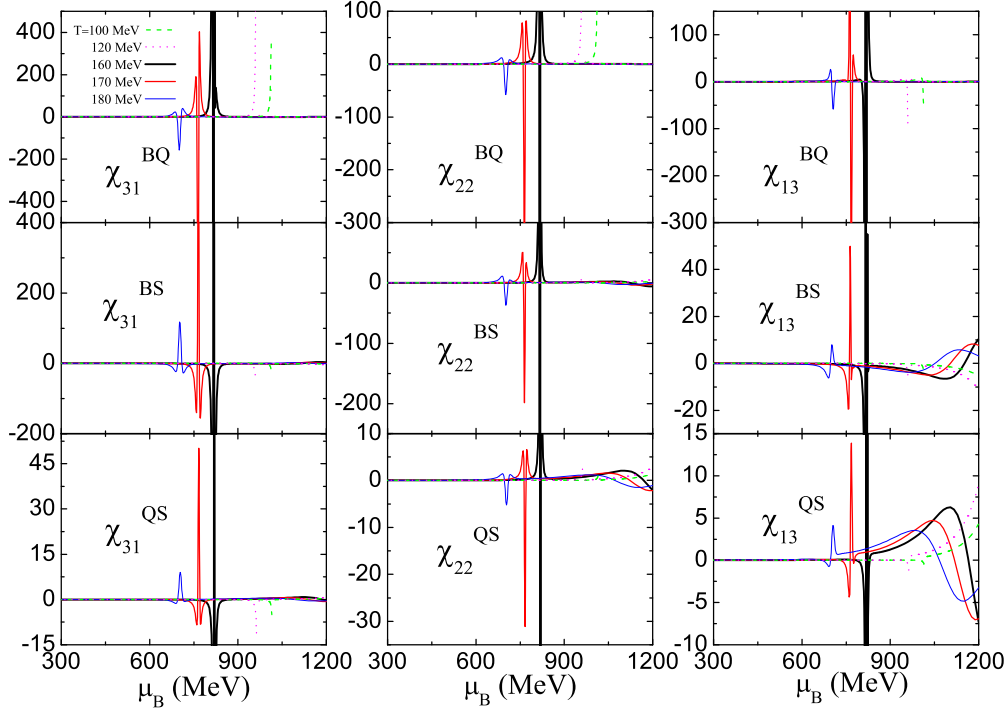
FIG. 1: (color online). Fourth-order correlations χ_{31}^{BQ} (top-left), χ_{22}^{BQ} (top-middle), χ_{13}^{BQ} (top-right), χ_{31}^{BS} (center-left), χ_{22}^{BS} (center-middle), χ_{13}^{BS} (center-right), χ_{31}^{QS} (bottom-left), χ_{22}^{QS} (bottom-middle), and χ_{13}^{QS} (bottom-right) as functions of the baryon chemical potential μ_B ($\mu_Q = \mu_S = 0$) with several values of temperature in the PNJL model.

the oscillating amplitudes of the correlations increase quickly when moving toward the QCD critical point, i.e., the temperature approaches to $T_c = 160$ MeV. All the fourth-order correlations between two conserved charges diverge at the QCD critical point. When the temperature is below T_c, the chiral phase transition is first-order and the correlations are discontinuous during the phase transition as shown by the dashed and dotted lines in Fig. 1. When the temperature is above T_c, the chiral phase transition is a continuous crossover due to finite quark current mass. Correspondingly, the correlations of conserved charges are also continuous during the QCD phase transition. As for the fourth-order correlations between two conserved charges, one notices that there are two maxima and one minimum in the curves of χ_{31}^{BQ}, χ_{22}^{BQ}, χ_{13}^{BQ}, χ_{22}^{BS}, and χ_{22}^{QS}, while there are two minima and one maximum in the curves of other fourth-order correlations between two conserved charges. Furthermore, it is seen that all the fourth-order correlations except for χ_{13}^{BS} and χ_{13}^{QS} vanish rapidly once

the thermodynamical system deviates from the QCD phase transition. In Fig. 1 we observe that χ_{13}^{BS} and χ_{13}^{QS} still have finite values at large baryon chemical potential, this is because the strange quark have relatively large current mass and its constituent mass can not be neglected even in the chiral symmetric phase.
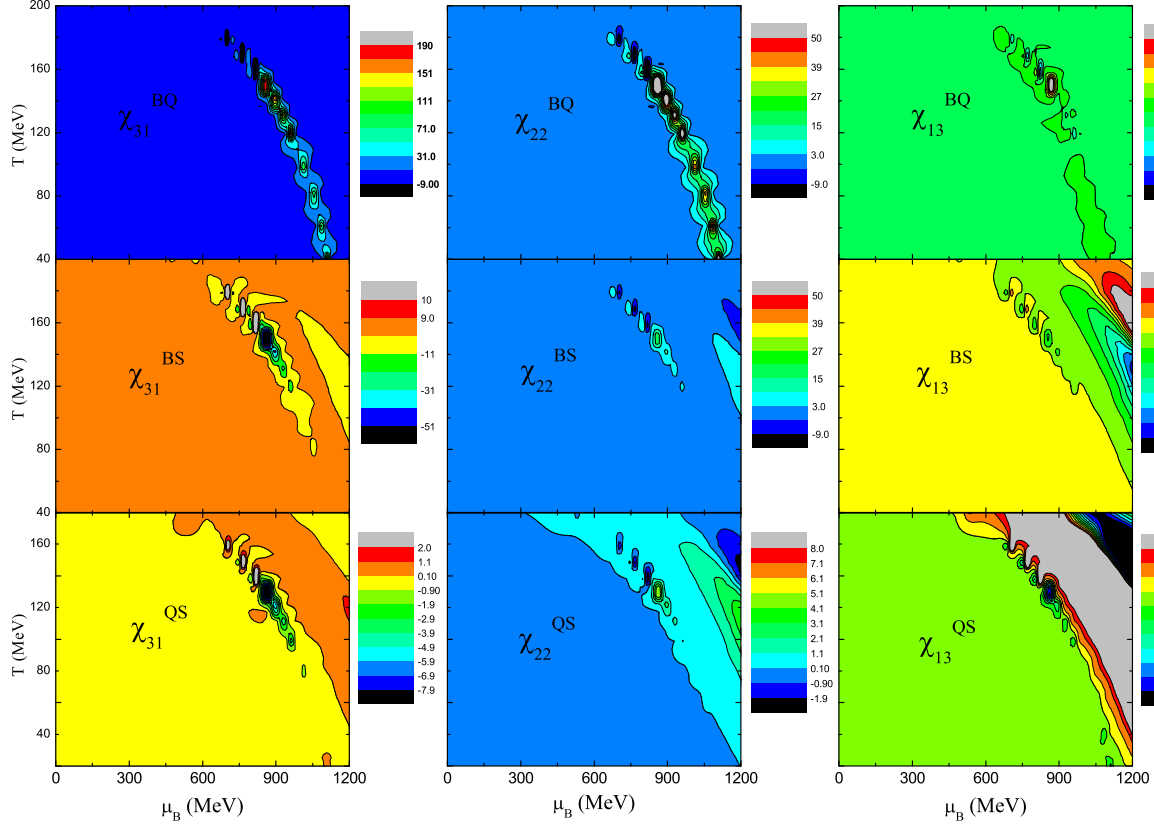

FIG. 2: (color online). Contour plots of the fourth-order correlations χ_{31}^{BQ} (top-left), χ_{22}^{BQ} (top-middle), χ_{13}^{BQ} (top-right), χ_{31}^{BS} (center-left), χ_{22}^{BS} (center-middle), χ_{13}^{BS} (center-right), χ_{31}^{QS} (bottom-left), χ_{22}^{QS} (bottom-middle), and χ_{13}^{QS} (bottom-right) versus temperature T and baryon chemical potential μ_B ($\mu_Q = \mu_S = 0$) in the PNJL model.

Fig. 2 shows the contour plots of the fourth-order correlations between two conserved charges as functions of the temperature and baryon chemical potential calculated in the PNJL model. We observe that the fourth-order correlations between two conserved charges are vanishing in the chiral symmetry broken phase, i.e., in the bottom-left region of every little plot. It is noticed that the chiral phase transition line is distinct in these plots and one
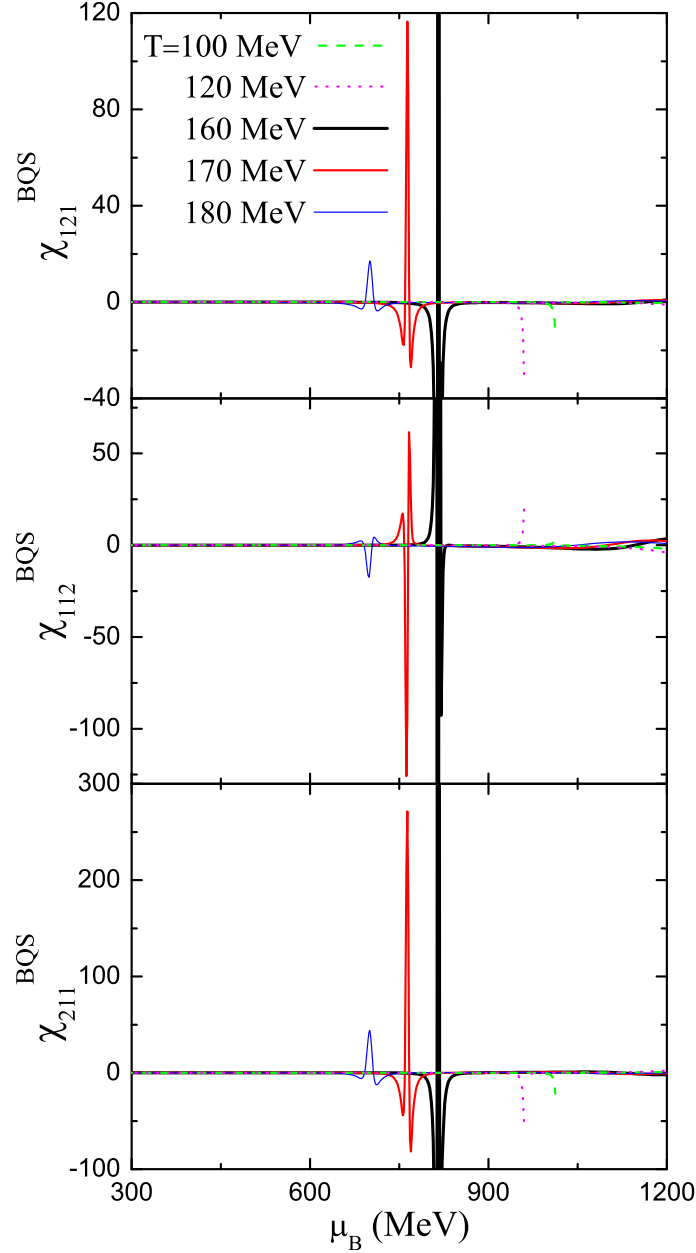
FIG. 3: (color online). Fourth-order correlations among three conserved charges χ_{121}^{BQS} (top), χ_{112}^{BQS} (middle), and χ_{211}^{BQS} (bottom) as functions of the baryon chemical potential μ_B ($\mu_Q = \mu_S = 0$) with several values of temperature in the PNJL model.

can easily recognize the region near around the QCD critical point, where the contour lines are dense. Comparing all these fourth-order correlations between two conserved charges, we notice that χ_{31}^{BQ}, χ_{22}^{BQ}, χ_{13}^{BQ}, χ_{31}^{BS}, χ_{22}^{BS}, χ_{31}^{QS}, and χ_{22}^{QS} are superior to χ_{13}^{BS} and χ_{13}^{QS} to be used to search for the critical point in heavy ion collision experiments, since the former

seven correlations have finite values only when the thermodynamical system is near around the QCD critical point.
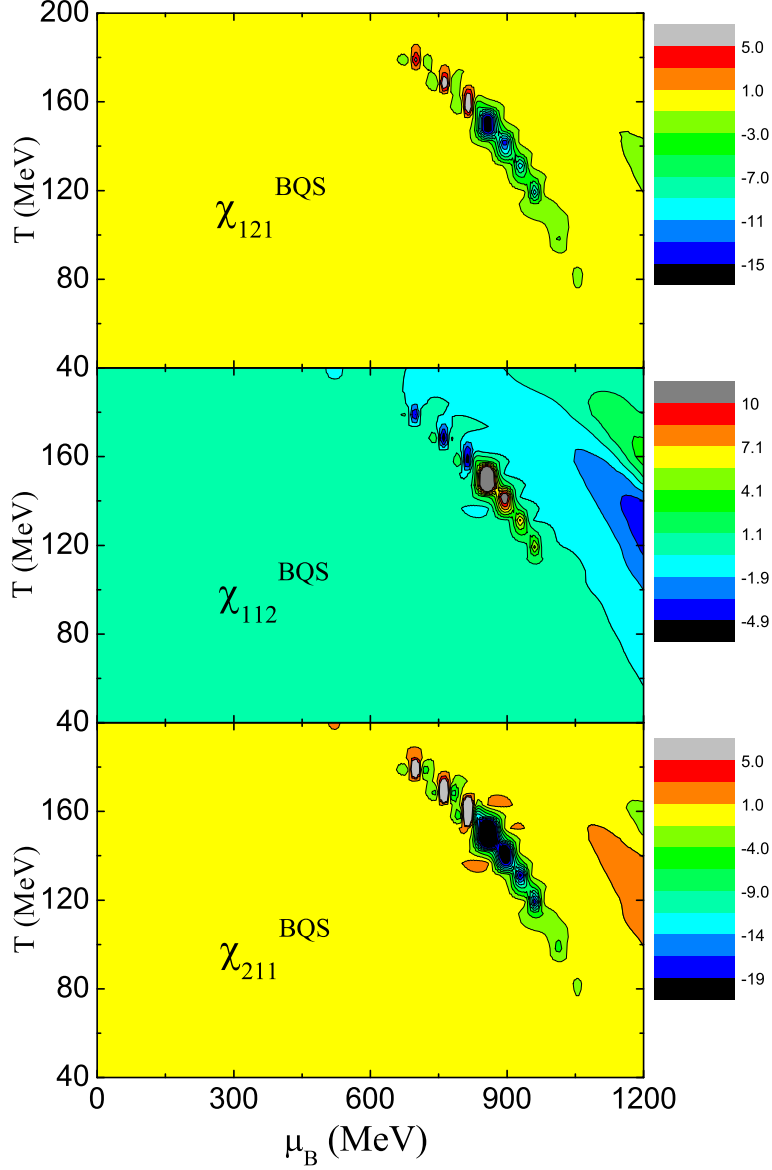

FIG. 4: (color online). Contour plots of the fourth-order correlations among three conserved charges χ_{121}^{BQS} (top), χ_{112}^{BQS} (middle), and χ_{211}^{BQS} (bottom) versus temperature T and baryon chemical potential μ_B ($\mu_Q = \mu_S = 0$) in the PNJL model.

In Fig. 3 we present the fourth-order correlations among three conserved charges as functions of the baryon chemical potential with several values of temperature calculated in the PNJL model. It is seen that the fourth-order correlations among three conserved charges

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are divergent at the QCD critical point same as those between two conserved charges. When the temperature is below $T_c = 160$ MeV, those correlations are discontinuous at the first-order chiral phase transition; while when the temperature is above T_c, they are continuous functions of the baryon chemical potential and change rapidly at the chiral crossover. It is observed that there are two minima and one maximum in the curves of χ_{121}^{BQS} and χ_{211}^{BQS}, and two maxima and one minimum in the curve of χ_{112}^{BQS}. One can also clearly notice that the fourth-order correlations among three conserved charges approach zero rapidly once the thermodynamical system deviates from the chiral phase transition.

In Fig. 4 we show the contour plots of the fourth-order correlations among three conserved charges as functions of the temperature and baryon chemical potential in the PNJL model. One can clearly recognize the QCD critical point in these three plots, which demonstrates that the fourth-order correlations among three conserved charges are quite sensitive to the singular structure related to the critical point. Therefore, the fourth-order correlations among three conserved charges are excellent probes to explore the QCD critical point in heavy ion collision experiments.

In summary, we have studied the fourth-order correlations of conserved charges, such as the baryon number, electric charge, and strangeness, at finite temperature and nonzero baryon chemical potential in the 2+1 favor Polyakov-loop improved Nambu–Jona-Lasinio model. It is found that the fourth-order correlations of conserved charges are divergent at the QCD critical point. When the temperature is below the critical temperature of the QCD critical point, the fourth-order correlations are discontinuous at the first-order chiral phase transition; while when the temperature is above the critical temperature, the fourth-order correlations of conserved charges are continuous with the change of the baryon chemical potential and oscillate rapidly at the chiral crossover. In the curves of the fourth-order correlations as functions of the baryon chemical potential, there are three extrema during the chiral crossover. Furthermore, we have given the contour plots of the fourth-order correlations of conserved charges in the plane of temperature and baryon chemical potential. The QCD critical point can be easily recognized in these plots. Comparing the fourth-order correlations, we notice that all the fourth-order correlations of conserved charges, except for χ_{13}^{BS} and χ_{13}^{QS}, are excellent probes to explore the QCD critical point, since these fourth-order correlations approach zero rapidly once the thermodynamical system deviates from the QCD critical point.

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